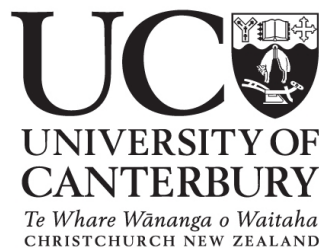


Energy Simulation and Reconstruction in String 63 for the IceCube Neutrino Detector

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1 Introduction

The remote neutrino telescope, IceCube, lies beneath the surface at the South Pole in Antarctica. It consists of a series of strings each equipped with 60 Digital Optical Modules (DOMs) every 17 meters[4]. The strings are placed approximately 130 meters apart. This creates an effective grid to make scientific observations. The DOMs were constructed to detect Cerenkov radiation emitted as high energy neutrinos interact with atomic nuclei[1]. Neutrinos interact with atomic nuclei to produce electrons. The electrons then undergo energy loss through Bremsstrahlung of photons[8]. The radiation loss occurs as a photon when the electron changes direction[6]. The photon then produces an electron and positron pair. The new electron releases further photons and more pairs are created. The process is repeated and grows exponentially[8]. This cascading effect continues until all the energy is absorbed. The length of the cascade is proportional to the energy of the original event[8].

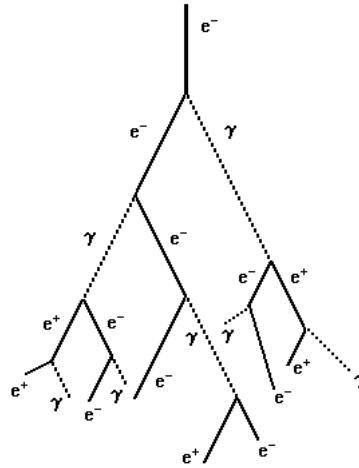


Figure 1: Emission of Photon from Electron for Positron and Electron Production[2]

The Cerenkov radiation is a blue light emitted when charged particles travel faster than the speed of light in a medium[10]. The light is blue due to the concentration of the radiation in the wavelengths of 475 nm which produce this color[8][9]. The Cerenkov radiation appears as a cone radiating from the electron's path[9]. The defining characteristics for Cerenkov radiation is the consistent angle in which it is emitted. As the electron proceeds the radius of the cone increases (See Figure 3).

These cascades are detected by the DOMs which record the Cerenkov radiation. The typical duration of an event is measured in nanoseconds, therefore timing precision is imperative for IceCube. The results are converted into a digital format and relayed to the surface via the IceCube cables for each string[4]. The data is then processed by a network of computers. To further understand the data, simulations are created mimicking events by setting off the flashers

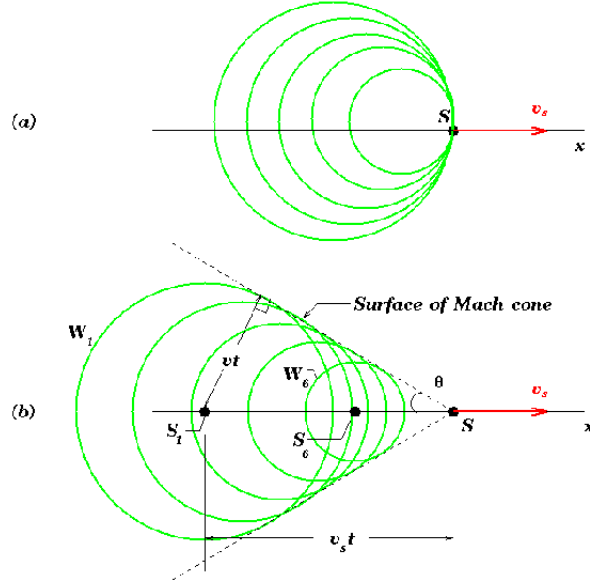


Figure 2: Cerenkov Radiation cone[3]

on the DOMs. With more variables controlled by the simulation, insight is given to real life events. The number of photons can be altered by adjusting the number of flashers activated. Comparisons can then be made under varying levels of brightness. Once simulations are completed, the ‘cascades’ can be reconstructed. This involves working backwards from generated cascades to find input values. This creates a system for checking the accuracy of the simulations. Further relationships can be monitored by doing a series of Monte-Carlo simulations and reconstructions. A correlation can be drawn between the energy detected for a full or half brightness scenario. It is hypothesized that when halving the brightness the energy range would be similarly halved. All ratios should be independent of ice depth as predicted.

2 Method

The analysis was completed using computer programs, under the workspace of *IceTray*. All the simulations were carried out for sting 63. This was chosen because it was centrally located and known to give representative results. At each DOM, 295 events were simulated. For a thorough range of results in ice depth, DOMs 10, 20, 30, 40 and 50 were evaluated. It is not wise to use the first and last DOMs as this would have skewed the results by Cerenkov radiation travelling beyond the reach of the detectors. This is further reviewed in the discussion section. The arbitrarily chosen full brightness was 8.88×10^{10} photons and half brightness was 4.44×10^{10} photons. In the cascade simulations 1.37×10^5 photons produce 1 GeV of energy. This translates to 650,000 GeV or 650 TeV for 8.88×10^{10} photons. Energy levels of TeV are considered high energy events. Half brightness is 325 TeV which still coincides as high energy.

The simulations were carried out by IceCube code written in C++ with a *Python* driver file. After the 10 simulations were all created they were reconstructed using a different set of code under *Python*. The results were then viewed by *ROOT*, a program created by CERN, a particle physics research institution in Europe. Root displayed the results in a series of histograms. The graphs reviewed in this study include *Cfirst*, *VertexRecoUPandel*, *VertexRecoUPandelMpe*, and *EnergyRecoHitNoHit_Energy*. These represent three methods of vertex reconstruction and an energy reconstruction method.

The *Cfirst* graphs took a reading of the X, Y, and Z coordinates for the vertex to the original event. These readings are based on the center of gravity for the event[7]. In the X value graph, the entry tally, peak mean, RMS error were displayed and thus recorded in the data entry. Records were uniformly taken on the Y and Z range of values. Once completed for the *Cfirst* graph, records were repeated for the *VertexRecoUPandel* and *VertexRecoUPandelMpe*. The Mpe graphs recorded multiple photoelectrons where as Spe graphs use single photoelectrons. The final parameters measuring the results were the energy spectrum. The records were displayed on the *EnergyRecoHitNoHit_Energy* graphs from the multiple and single photon view point. (See Appendix for Spe energy reconstruction graphs) The *HitNoHit* method recorded the probability that the DOM being evaluated will be hit with a photon[7]. The energy graph for this reading recorded the average energy for the cascade overall. This allowed the full and half brightness to be compared. All these results from the various graphs were compiled into a finalized table that focused on the energy and RMS values. The results are displayed in the table below.

3 Data

DOM Numbers	Method used	Energy Full Brightness	RMS Error	Energy Half Brightness	RMS Error	Ratio
10	Spe	4.53×10^5	5.87×10^4	2.21×10^5	2.97×10^4	49%
	Mpe	4.95×10^5	8.6×10^3	2.97×10^5	1.11×10^4	60%
20	Spe	7.61×10^5	6.72×10^4	3.92×10^5	3.89×10^4	52%
	Mpe	6.56×10^5	1.5×10^4	4.31×10^5	9.6×10^3	66%
30	Spe	6.97×10^5	5.46×10^4	4.18×10^5	4.17×10^4	60%
	Mpe	8.36×10^5	1.21×10^4	5.84×10^5	1.39×10^4	70%
40	Spe	1.25×10^6	1.03×10^5	7.3×10^5	7.26×10^4	59%
	Mpe	8.88×10^5	1.05×10^4	6.13×10^5	1.46×10^4	70%
50	Spe	1.26×10^7	3.66×10^6	6.93×10^6	1.39×10^6	55%
	Mpe	1.65×10^6	4.63×10^4	1.22×10^6	1.47×10^4	73%

Table 1: Energy reconstruction for full and half brightness. At full brightness 8.88×10^{10} photons were used. Half brightness followed at 4.44×10^{10} photons. The ratio is a comparison of full brightness to half brightness energy values.

4 Results

Since this is one of the first studies on full and half brightness effects on the energy output, it is hard to establish an acceptable range. Despite this, conclusions can be drawn and patterns detected in the results. In an overall stance of the data obtained, it can be seen the Mpe results were not as reliable as the Spe results as expected[7]. This further confirms previous studies that despite the theory that more data points give a better estimate of energy, the single photoelectron seems to be more accurate. When comparing the half brightness with full brightness for Mpe's they differed from 60% to 74%. The range was much smaller for the Spe beginning at 49% and peaking at 60%, Mpe's minimum. The average Mpe's ratio was 68%, the average of Spe's was 54.8%.

In the first layers of ice surrounding DOM 10 the energy range is the closest to 50% for both the Mpe's and Spe's. As the layers deepened the results become increasingly varied. For the Mpe there is a steady climb as the energy remains

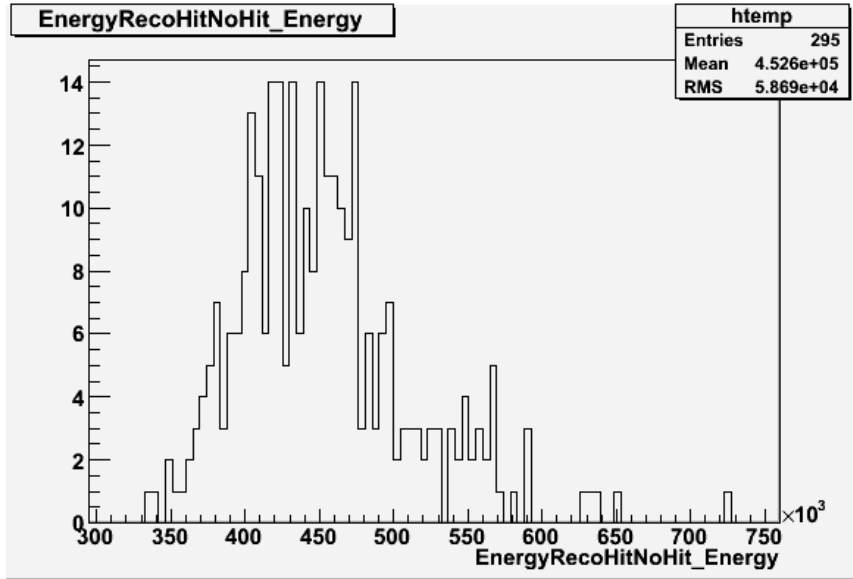


Figure 3: DOM 10 Full Brightness Energy Histogram.

at a higher ratio. A similar pattern appeared to be happening in the Spe except that as it reached DOM 50 the energy ratio decreased by 3%. The relevance of this change is best evaluated in a broader context. These results should also be compared to the graphs of the RMS data. It can clearly be seen that as the ice deepens the RMS error significantly peaks around DOM50. The RMS error was consistently one degree of power lower than the energy results. However at DOM 50 the energy levels spiked as did RMS errors (See Figure 4). Given this, the 3% decrease in energy ratio of Spe data could be absorbed. While the RMS error is still relatively low, it should be considered in the accuracy of the results. This trend of the energy increasing towards DOM 50 was carried through from full to half brightness. When IceCube is completed it is expected that energy levels will be measured more accurately by one degree of magnitude.[1]

5 Discussion

From the characteristics of the data, and given the medium used, the results can most likely be explained because of the properties of the ice. The IceCube Collaboration made an attempt to eliminate errors by placing the first strings 1,450 meters below the ice, well out of the way of the firn layers.[1] These upper layers are much more porous and readily scatter light. As the depth increases, the results of built up snowfall and pressure on the ice can be seen. Distinguishable layers are visible displaying the different freezing and thawing cycles that happen annually on the ice's of Antarctica. As one descends in the layers, the density will increase and air is pushed out. At no depth will this effect be eliminated. Thus despite a low starting depth, variations in density are unavoidable.

As the density increases the energy levels climb to higher values. In the

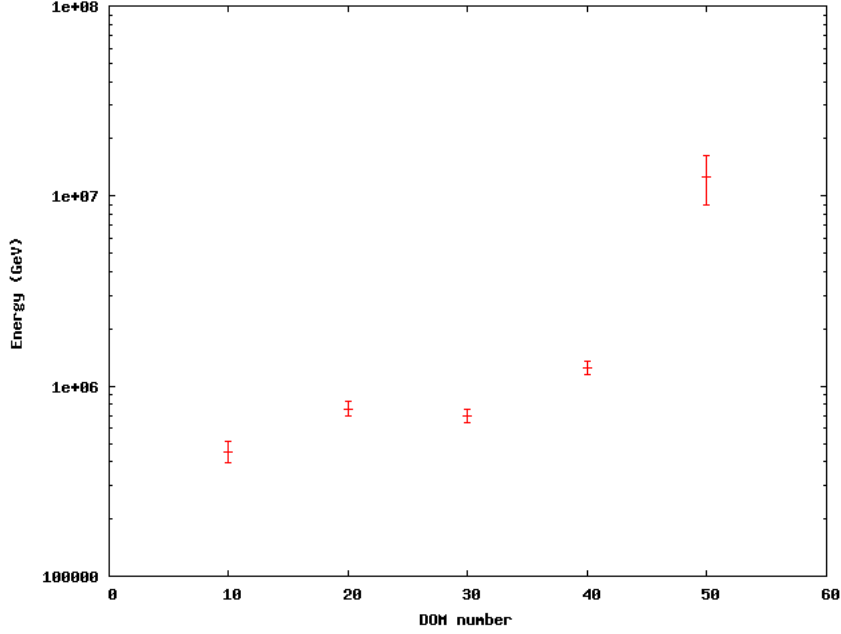


Figure 4: Energy vs DOM number with RMS error bars from 1-60 with 60 being the deepest DOM. Reconstruction is of Spe Data for Full Brightness with 8.88×10^{10} Photons.

first DOM the light was closest to exactly half the energy when the number of photons were halved. It can be postulated that this is because the ice was denser and thus able to transmit more photons. The number of air bubbles trapped in the ice decreases as pressure levels rise causing them to collapse. If the medium has less scattering from air bubbles, the energy levels are maintained at higher levels for longer. The trend continues as by DOM 40 and DOM 50 energy levels are at their highest. Not only do energy values increase with depth but so do energy ratios. Larger RMS errors allowed for more variation in results.

Questions arise from the data for the DOM 40 as there is a known dust layer around the DOM 35[7]. The effects of this dust layer may also be impacting the results in uncontrollable ways. From a visual perspective of the cascades it appears as if fewer photons are being detected above the vertex. The photons are reaching greater depths below the vertex as time progresses. Unfortunately, avoiding the dust layer is only possible by a deeper more expensive observatory which could find further dust layers still.

Below the dust layer there is a distinctive jump in the reconstruction energy range even with the same number of photons being emitted. The detection of higher energy values and conductive properties of the ice causes more photons to be detected in larger cascades. If there are more photons, there is a higher probability that a DOM will be hit in any given cascade. As a result, more DOMs send data to the surface. While working with more data the results are more likely to hold a better representation. Each simulation and reconstruction consisted of 295 events yet the lifetime or sustainability of the decay could not be controlled.

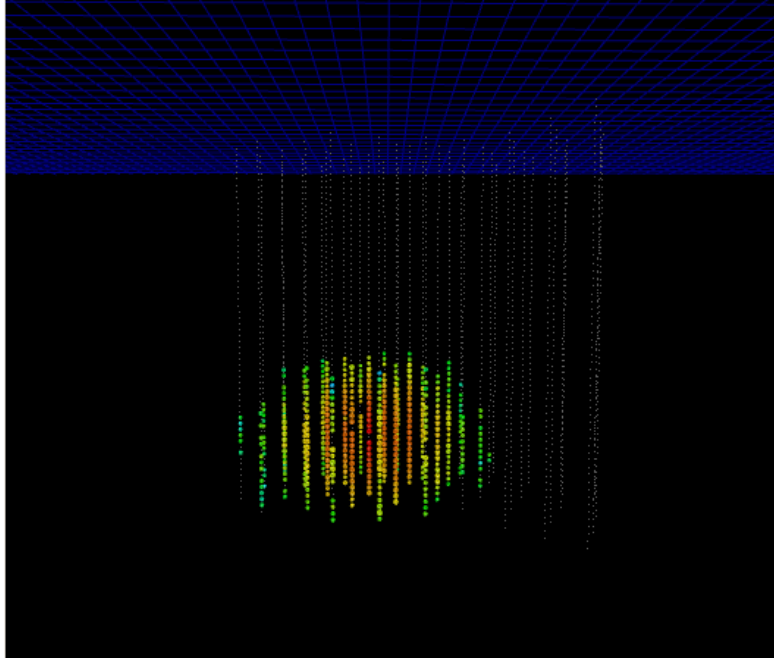


Figure 5: DOM 50 full brightness energy reconstruction cascade. Red represents the origin of the event progressing to green as the cascade continues.

It is interesting to note that the simulations and reconstruction generation took dramatically longer for DOM 50 than it did for any other. The visual cascade representation also had more DOMs being reached further from the vertex. This leads to photons extending beyond IceCube’s detection. Despite the already higher levels of energy detected, there is a high probability that it would be even greater if more of these escaping photons were detected. The significance of these lost results may be minor but is unknown. It is one of the limitation in the geometry of IceCube.

The combination of results implies that the reconstruction energy of very high energy events being detected will have serious differences depending on the depth in the ice. If it is deeper down, the energy will be closer to the initial energy of the event. As stated before, the length of the cascade is dependent on its initial energy. It must be taken into consideration if an event is closer to the bottom of the detector where the photons and electrons cascade beyond the reach of the DOMs. There are more complicated programs that take these ice properties into consideration. Due to time constraints, these applications were not feasible. However, this work does assert the necessity of running these further simulations if more accurate results on energy levels are desired.

6 Conclusion

This investigation into the varying energy ranges associated with brightness levels and ice depth provokes further studies. It was found that the energy ranges that were presumed to be directly halved as the number of photons emitted was cut were in fact ranging from 48% to 70%. The single photoelectron results were closer to the 50% range, maxing out at 60%. Further analysis on the Mpe results could prove otherwise but it is currently accepted that the Spe data held more accurate results. The variation in energy ratio was proportional to the ice depth. Energy ranges similarly varied with associated depths. For the full brightness the energy range varied by two degrees of magnitude where as half brightness varied slightly less at one degree of magnitude.

The lowest energy ratios were found at DOM 10 then steadily increased to DOM 40 and 50. The Spe's decreased slightly at DOM 50 where the Mpe results continued to climb. The trends can be attributed to ice properties at greater depths being more conducive to photons radiating further. It is at these depths under immense pressure that the number of air bubbles decreases causing less energy being lost or absorbed. Under different more sophisticated reconstruction methods the simulations and reconstruction results might vary with the ice properties being factored in. Efforts should be made to better understand the nature of the ice and its effect on energy levels.

A Appendix

Energy reconstruction histograms for Spe data at full brightness

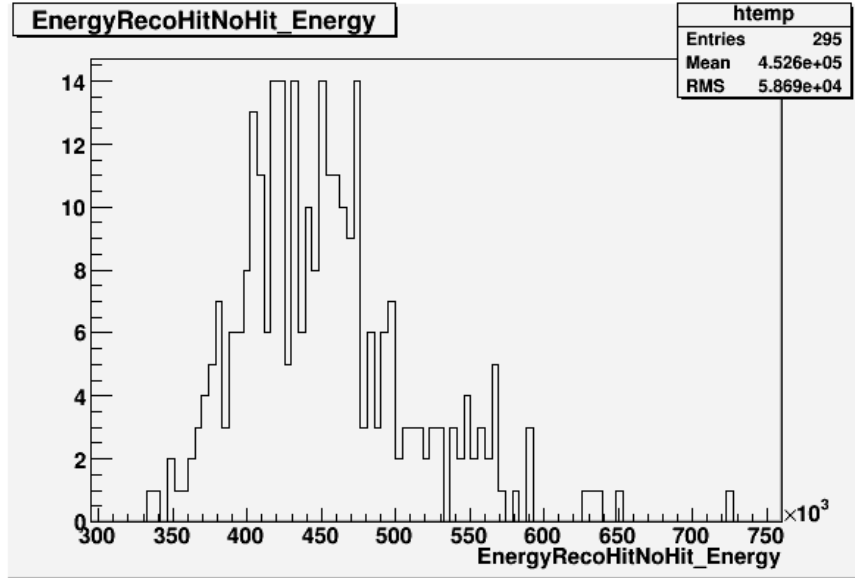


Figure 6: DOM 10 Full Brightness Energy Histogram

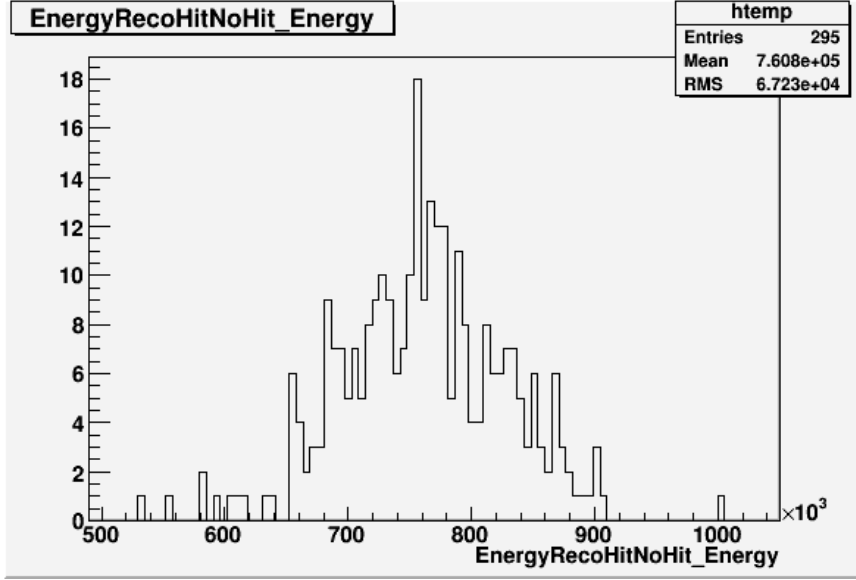


Figure 7: DOM 20 Full Brightness Energy Histogram

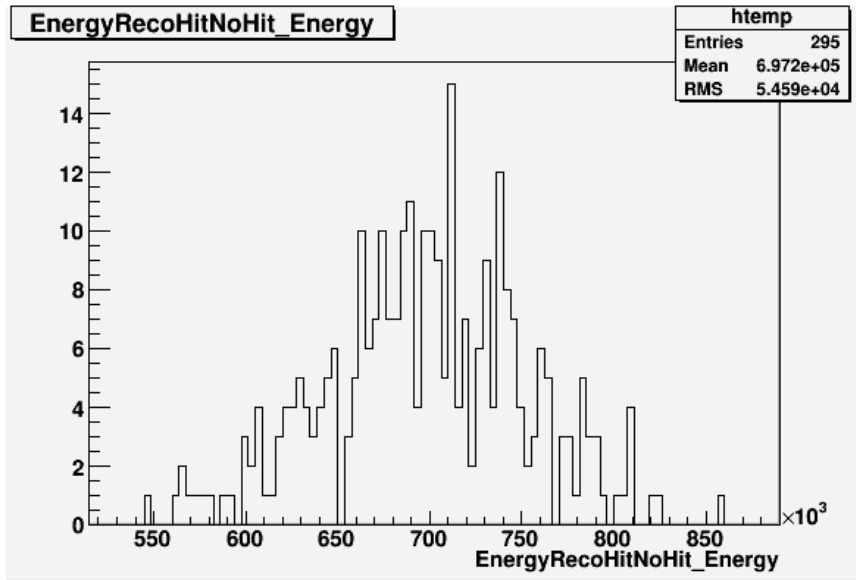


Figure 8: DOM 30 Full Brightness Energy Histogram

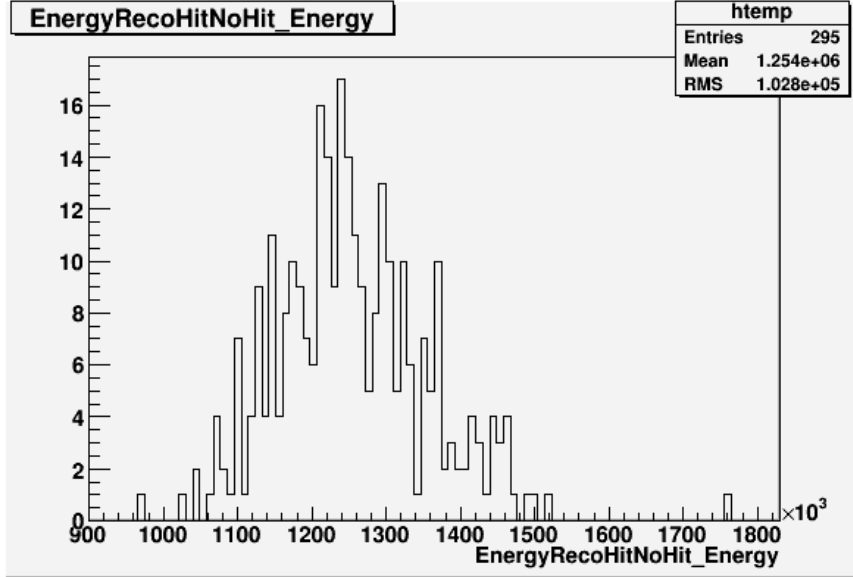


Figure 9: DOM 40 Full Brightness Energy Histogram

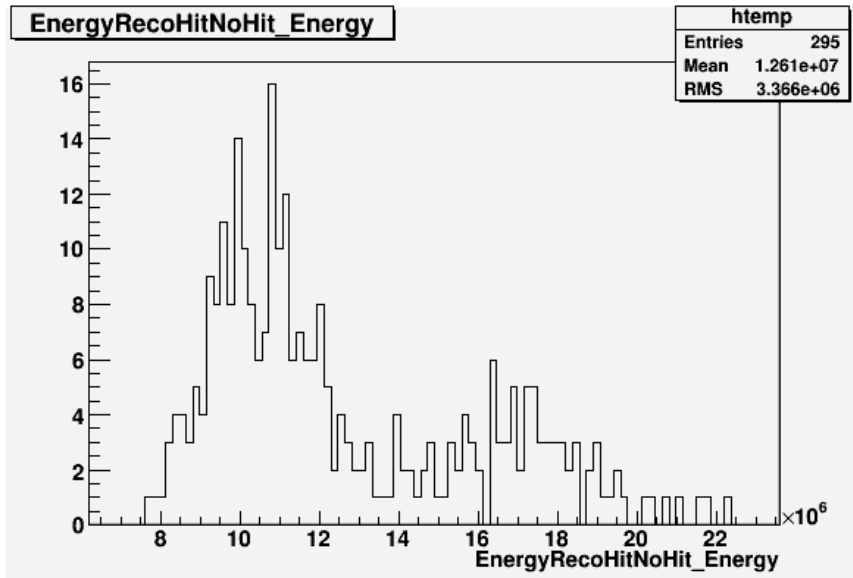


Figure 10: DOM 50 Full Brightness Energy Histogram

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